Large Antenna Arrays for the DSN and Radio Astronomy

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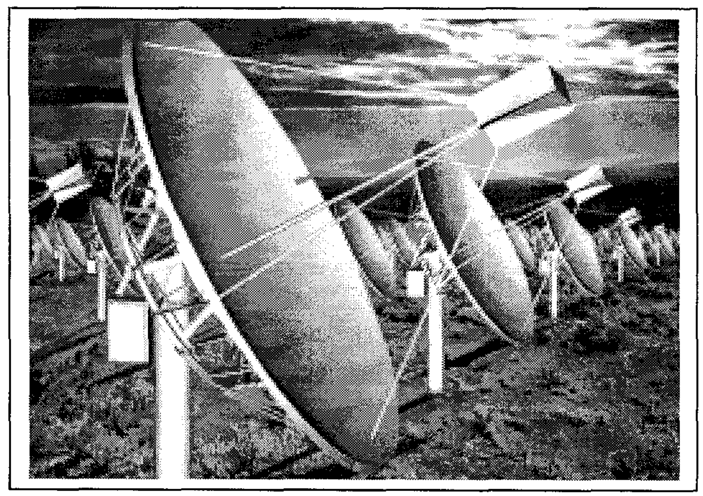
August 9, 2001

- The Existing DSN and Future Arrays
- What a Square-Km Array (SKA) Could do for DSN
- Technology Development for Large Arrays
- Costs of Large Arrays
- Situation Summary
- Next Steps for JPL



Comparison of Existing Large Antennas and Future Arrays

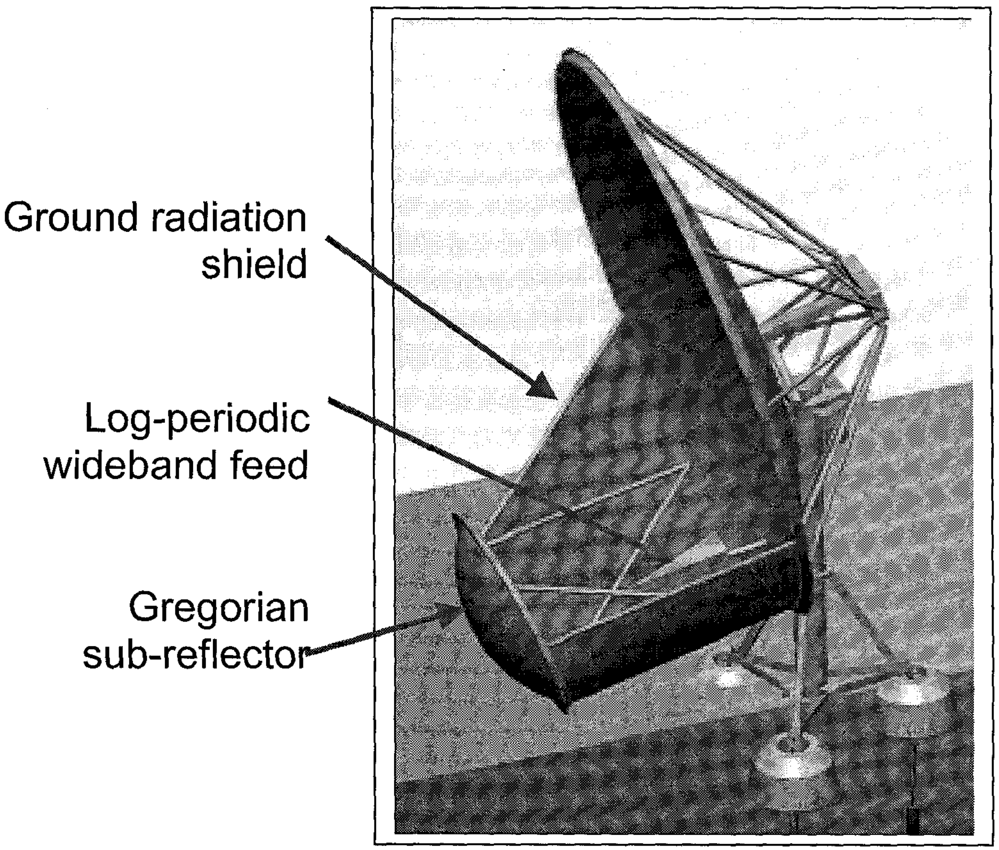
Antenna	Elements	Effective Area	Upper Frequency	Tsys	A/Tsys	Year Finished
DSN 70m	1 x 70 m	2,607	8 GHz	18	145	1965
GBT	1 x 100 m	5,700	100 GHz	20	285	2000
VLA	27 x 25 m	8,978	43 GHz	32	280	1982
Arecibo	1 x 305 m	23,750	8 GHz	25	950	1970
ALMA	64 x 12 m	4,608	800 GHz	50	92	2011
ATA	350 x 6 m	6,703	11 GHz	35	192	2005
DSN Array	1600 x 8m	51,200	32 GHz	25	2048	2010
SKA	14,000 x 10m	700,000	32 GHz	35	20,000	2015

SKA Communication Improvement Relative to DSN 70m Antennas

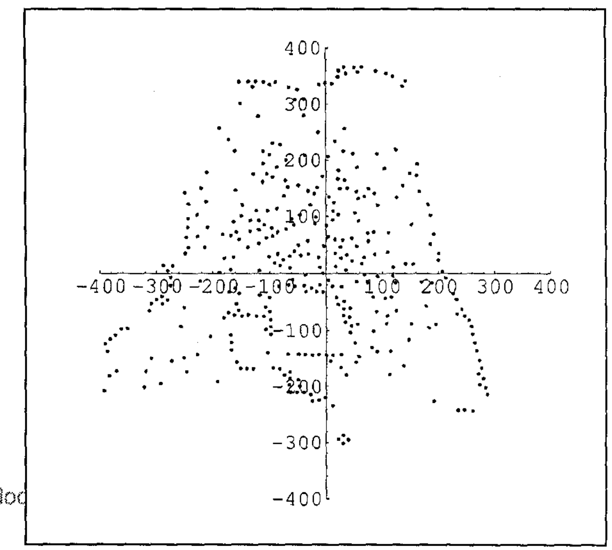
Antenna	dB Improvement at 8.4 GHz	dB Improvement at 32 GHz
DSN 70m	0	+6 dB
DSN 34m	-6 dB	0
SKA	**21.3 dB**	**27.3 dB**

What is the Allen Telescope Array, ATA?

- 350 x 6m offset hydroformed paraboloids
- Instantaneous bandwidth of 0.5 to 11 GHZ
- A joint project of the SETI Institute and UC Berkeley
- Privately funded to cost approximately $20M
- First array testing in 2003; completion in 2005



Hat Creek, CA site (above) and array configuration (below)



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What is the SKA?

- An international project to design a very large area array for radio astronomy in the cm wavelength range.
- The web site, http://www.skatelescope.com, contains science justification and links to activities in several countries
- US approach is a large array ($\approx$10,000) of small ($\approx$10m) antennas , organized into a 1000km diameter spiral of $\approx$100 close packed stations
- Next scientific and technical meeting, *The SKA: Defining the Future*, Berkeley, CA, July 9-12. See web site for program and registration.
- Chairman of the International SKA Project, Ron Ekers, will meet with JPL Director, Charles Elachi, and give **a talk at JPL, August 16, 10am, in Bldg 167 conference room.**

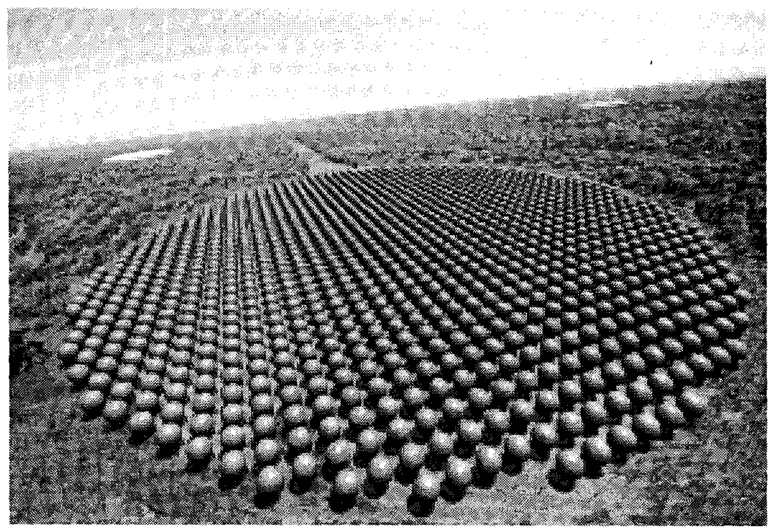
Key Specifications

- Aeff/Tsys > 20,000 m^2/K

(1 square km with Tsys=50K)

- Frequency, 0.15 –20 GHz
- Resolution 35 nano-radians

(5km beam at 1 A.U. at 20GHz)



A Road Map for the United States' Development Efforts on the Square Kilometer Array

PREPARED BY THE US SKA CONSORTIUM

California Institute of Technology (including JPL)
Cornell University (including NAIC)
Harvard-Smithsonian Center for Astrophysics
Massachusetts Institute of Technology (including Haystack Observatory)
National Radio Astronomy Observatory
Naval Research Laboratory
Ohio State University
SETI Institute
University of California, Berkeley
University of Minnesota

Draft 2: March 28, 2001

Contents

1 Executive Summary **i**

2 What is the SKA? **1**

3 Key Science Areas that Drive SKA Technology **3**

4 The SKA as an International Project **6**

5 The U.S. Large-N Design Concept **8**

6 Possible NASA Interest in the SKA **9**

7 The Technical Challenges: U.S. Development Efforts and Payoffs **10**

8 The U.S. plan **16**
8.1 An Implementation Plan that Leverages Ongoing Activities 16
8.2 Suggested Timeline for SKA Technical Development 17
8.3 Suggested Funding Plan For SKA Technology Development 19
8.4 Management Plan 20

9 Outreach **20**

10 Requested Actions from the NSF **20**

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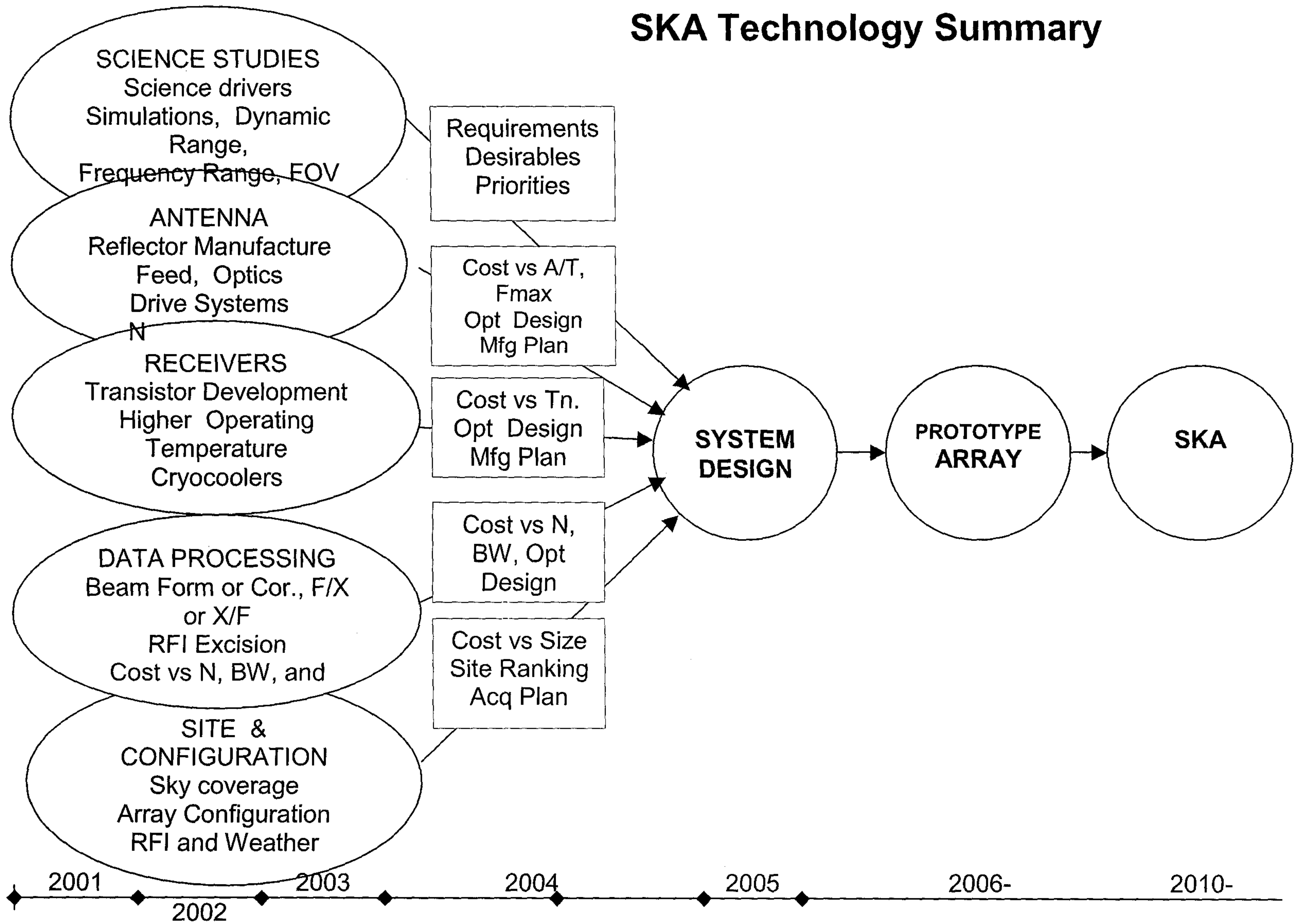
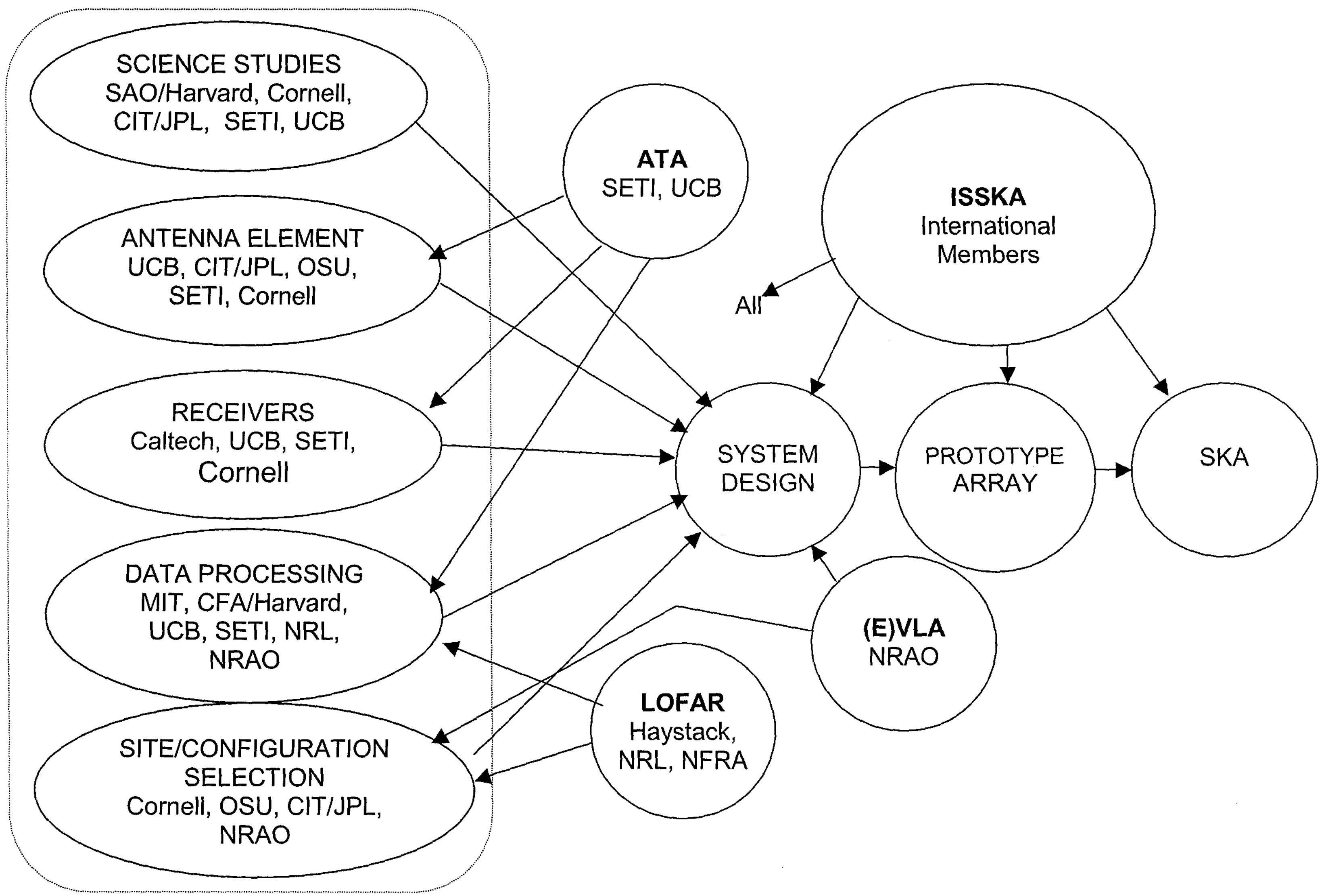
SKA Technology Summary



USSKA

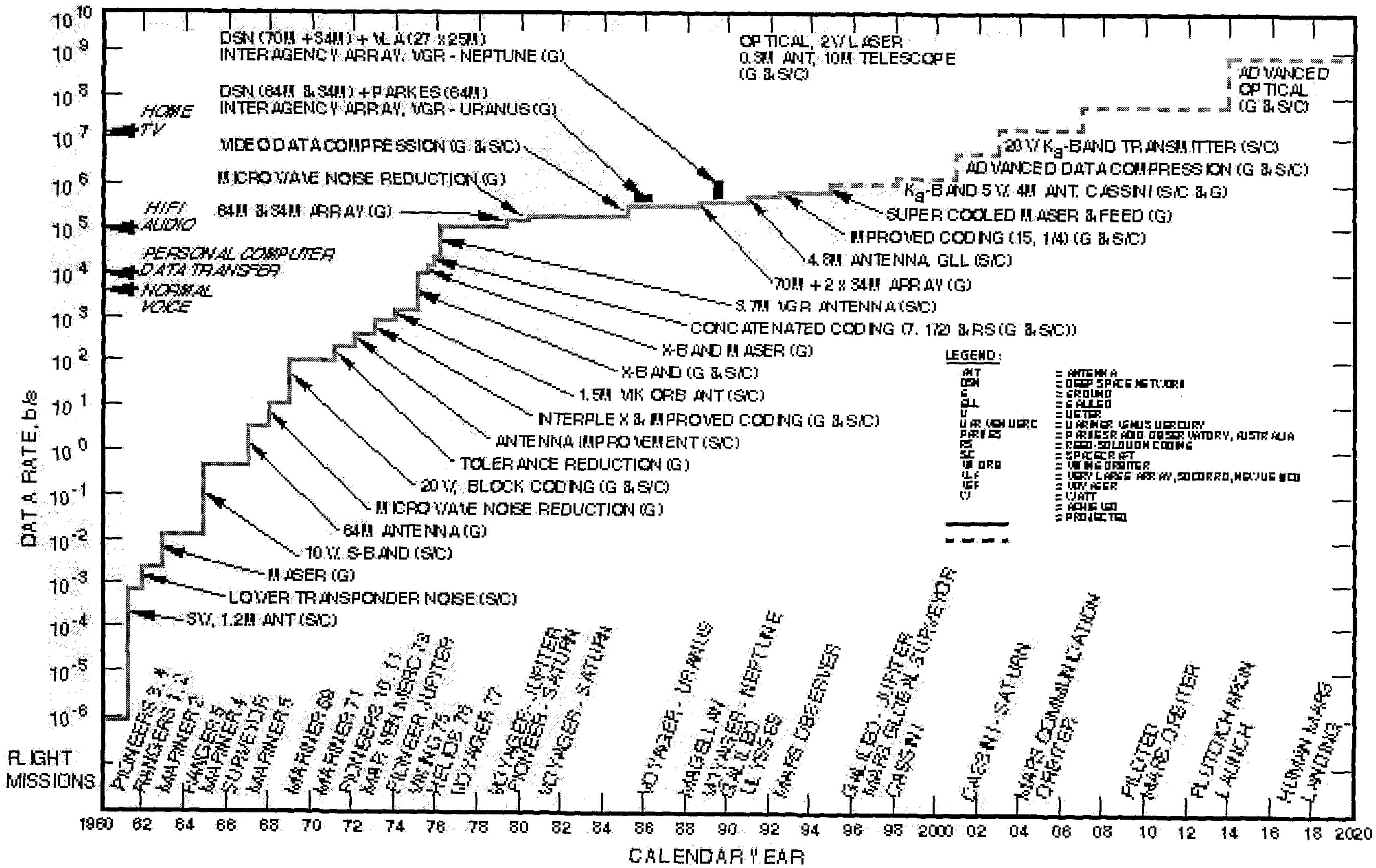
SKA Organizational Summary



PROFILE OF DEEP SPACE COMMUNICATIONS CAPABILITY

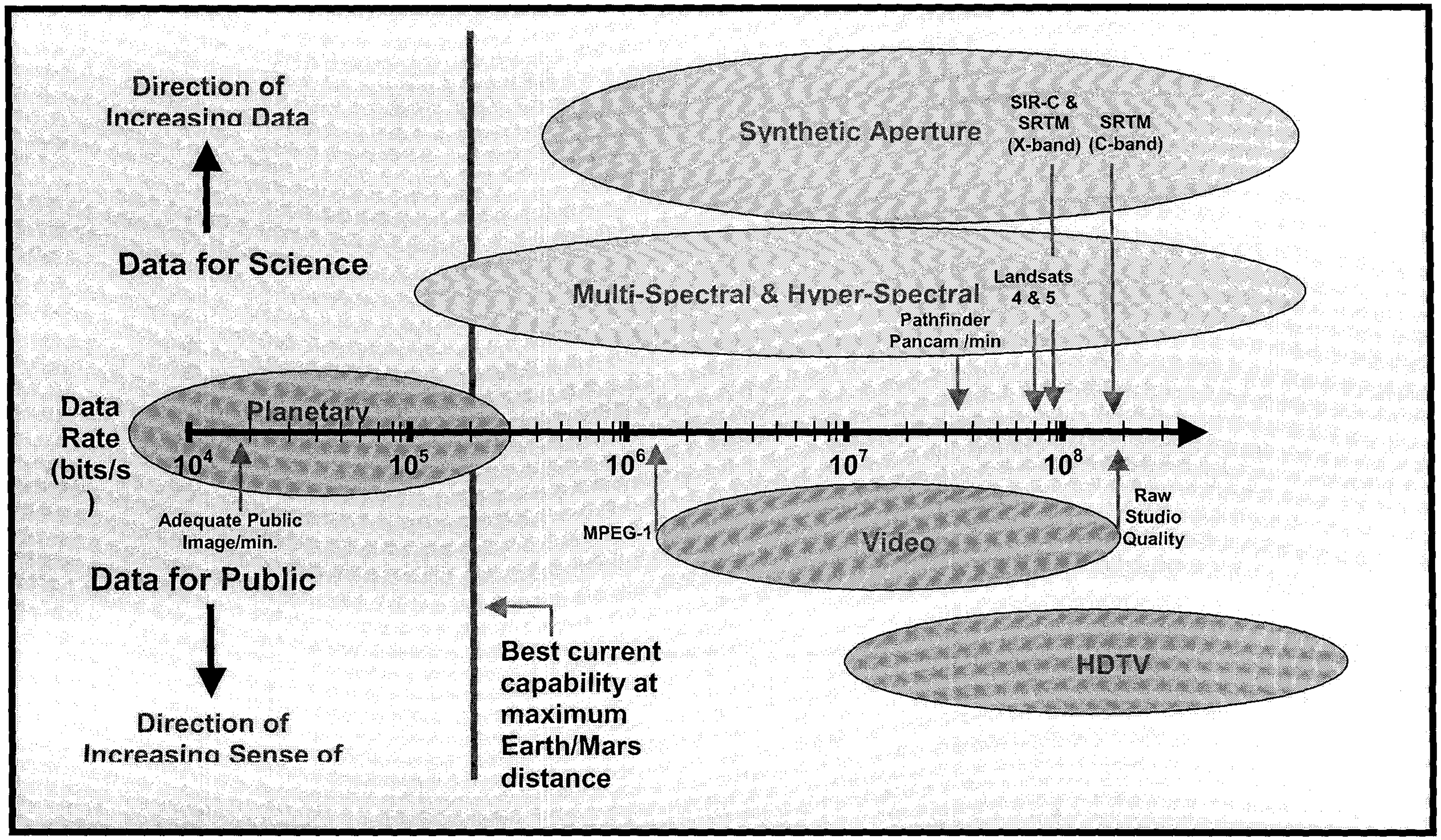
SPACE-TO-EARTH

EQUIVALENT IMAGING DATA RATE CAPABILITY AT JUPITER DISTANCE - 750 MILLION KILOMETERS



Increasing Data Rate to Deep Space

- Increasing data rate to deep space will remain the focus for major investment over the next decade
  - It will also be critical to invest in information systems architectures and applications to make use of the increased capability with minimal cost impact to science missions
- Data rate requirements for science and the public are factors of 10 to 100 higher than can be provided with the present DSN



New DSN Technology Thrusts

The future DSN will utilize an optimum combination of new technologies to increase data return, reduce costs, and improve mission robustness

Internet Network Architecture

- Decrease mission costs by adoption of standardized protocols
- Enhance productivity by making mission data easily accessible.
- Enhance reliability by multiple-paths.
- Reuse of software and hardware.

Orbiting Relay Satellites

- Provides orbiting relay with high-gain antenna to increase data transmission rate for outer planet missions
- Allows lander assets to be devoted to science instruments rather than direct to earth communications.

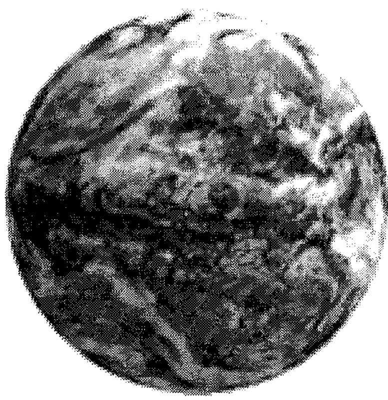
Optical Communications

- Very large increase in transmitter gain facilitates very high data rates with low power
- Explosion of new optical communication components and new era of astronomical instruments provides the core technology for optical space communications.
- Challenges are precision pointing, solar radiation, and weather diversity.

Microwave Arrays

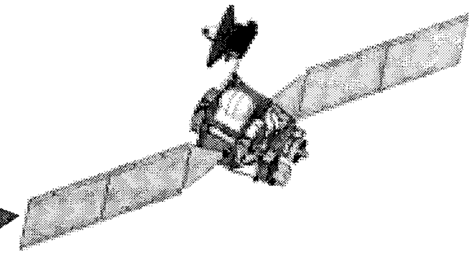
- Can provide large increase in data rate by increased receiving aperture on earth
- Minimum cost per unit area by choice of optimum diameter antenna element
- Advantages of multiple beams, soft failure, weather diversity, and expandability
- Synergistic with new developments in radio astronomy such as ATA, SKA, and ALMA.

Mars Telecommunications Examples



Orbiter Direct-to-Earth Link

- **10 kbps - 1 Mbps to 34m @ 2.7 AU**
- **Example: MGS**
  - 25 kbps, 1.5 m HGA
  - 25 W TWTA

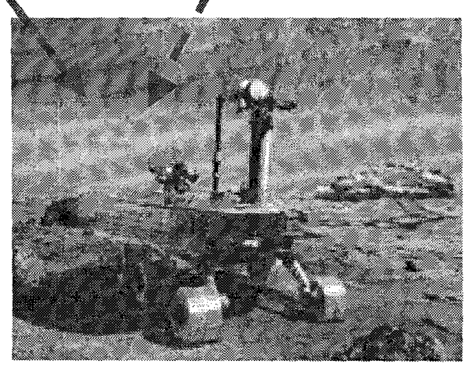


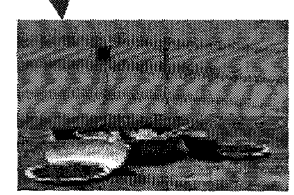
Lander Relay Link

- **100 kbps-1 Mbps**
- **Example: M ER**
  - 128 kbps, Omni UHF antenna
  - 10 W SSPA

Large Lander Direct-to-Earth Link

- **1 kbps - 10 kbps to 70m @ 2.7 AU**
- **Example: MER**
  - 2 kbps, 28 cm HGA
  - 15 W SSPA





SKA Applied to Deep Space Communications

Use SKA to increase data rate by 100+

- Movies, instead of images
- Robotic, virtual-presence exploration of outer planets
- High-resolution multi-spectral imaging
- High-resolution synthetic-aperture imaging of planets
- Short-life, high-data-rate missions to hostile environments (Venus)
- Enables new science missions requiring high data rates

Use SKA to reduce spacecraft mass, power, and cost

- Enables much smaller, lower cost spacecraft
- Reduce or eliminate spacecraft pointing requirements
- Provide low-data monitoring during critical reentry times
- Use to support spacecraft in distress

SKA Applied to Deep Space Navigation

Use SKA to obtain real-time, plane-of-sky, spacecraft position simultaneously with range and Doppler-determined velocity

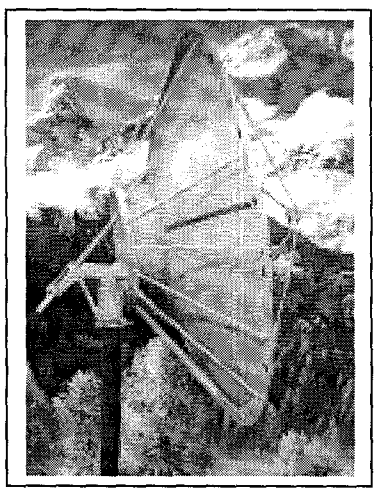
- At 2 AU an array with 500 km baselines and a frequency of 32 GHz has a linear beamwidth of 6km allowing 600m position accuracy.
- The array provides of the order of 5,000 times better angular resolution than the DSN 70m antenna.
- At present spacecraft navigation relies on range and doppler with only coarse angular data. This can result in errors in position determination at critical re-entry or boost orbits as occurred on a recent Mars mission.
- Present VLBI measurements of spacecraft position are not real-time which limits applications.
- An array in multi-beam, multi-frequency transmit mode allows establishment of a distant position reference system without time of flight delay.

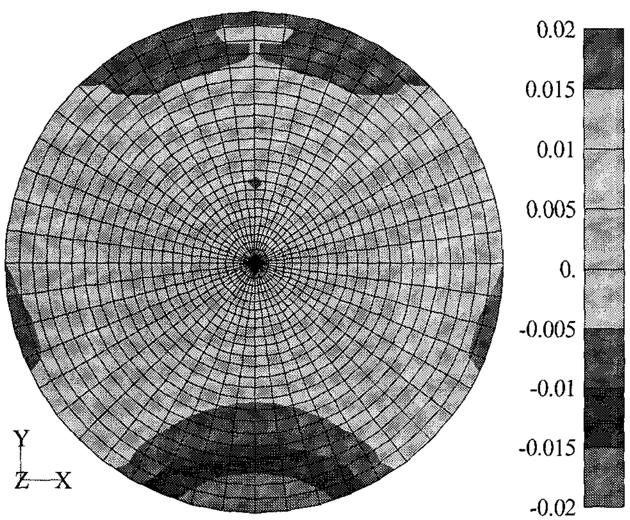
Hydroformed Aluminum Antennas

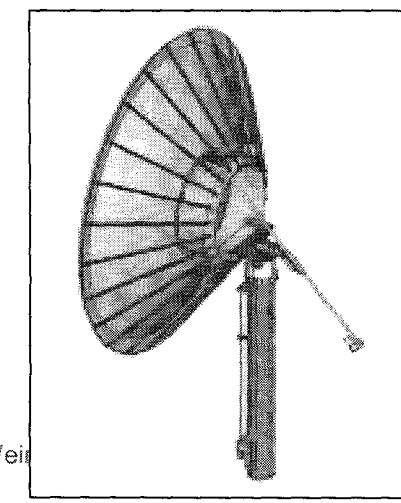
Hydroforming is a process of using a fluid or gas at very high pressure to force aluminum sheet to conform to a mold. The result is a stiff, accurate, and low cost reflector.

JPL has performed a structural analysis of 5m and 8m hydroformed reflectors manufactured by www.andersenince.com and has found that the wind and gravitational distortions would allow operation at frequencies as high as 100 GHz.

Example	Antenna Diameter	Cost per Antenna	Cost per m^2	Cost per km^2
New 70m DSN antenna	70m	\$100M	\$40.8K	\$40.8B
25m VLBA antenna	25m	\$3M	\$9.6K	\$9.6B
6m ATA antenna	6m	\$30K	\$1.7K	\$1.7B
Target SKA cost	10m	\$30K	\$600	\$0.6B
Hydroformed DBSTV antenna	4m	\$2.8K	\$350	\$0.35B
Aluminum, 3mm thick sheet	Any	NA	\$30	\$.03B

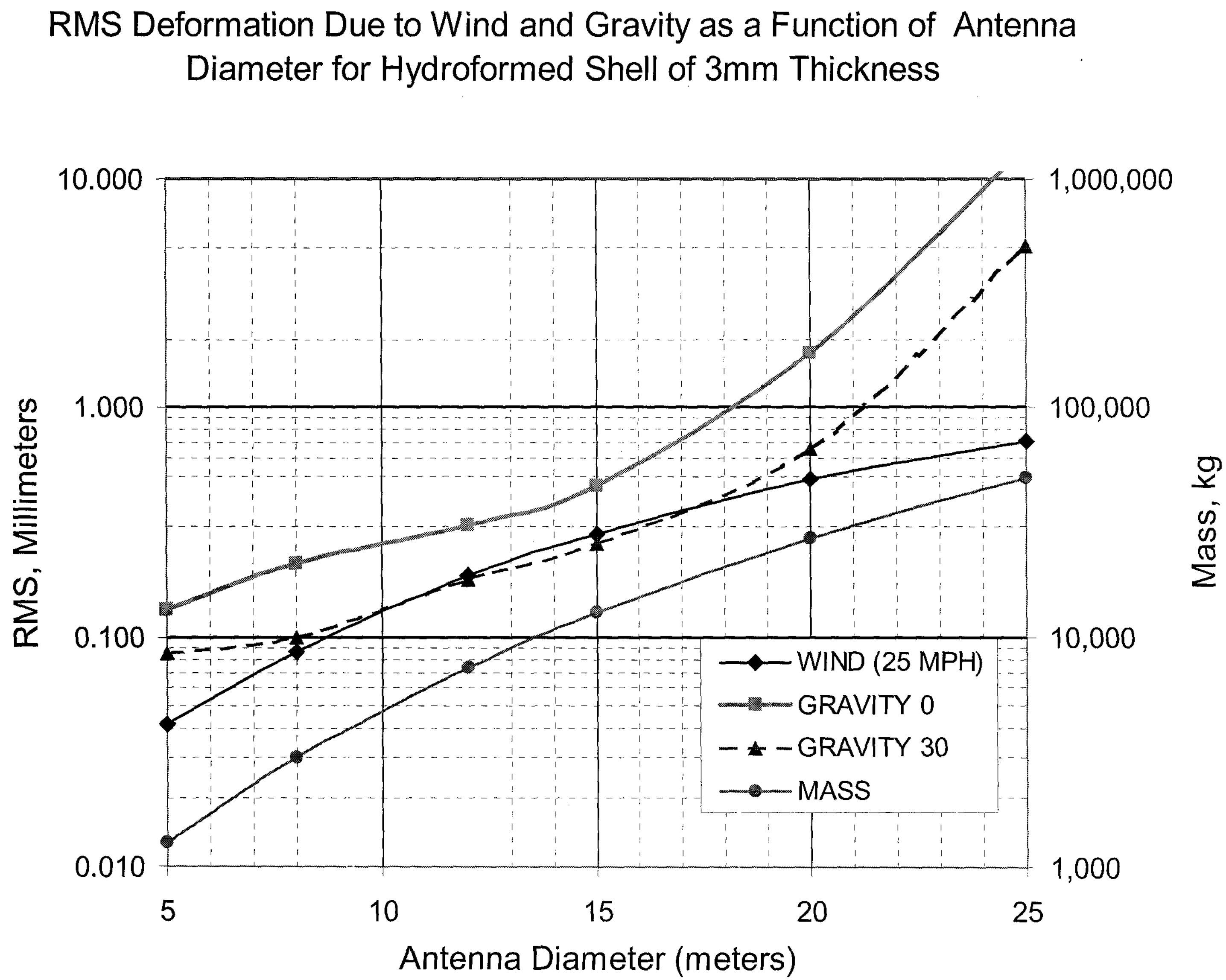






JPL/Swales Finite-Element CAD Analysis of Hydroformed Shells

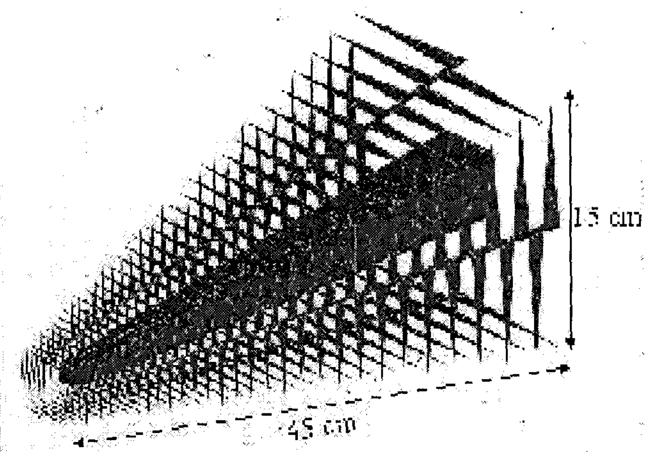
(0.1mm RMS is Required for an Efficient 100 GHz Antenna)



0.5 to 11 GHz Dual-Polarized Feed Developed by SETI/UCB for the ATA

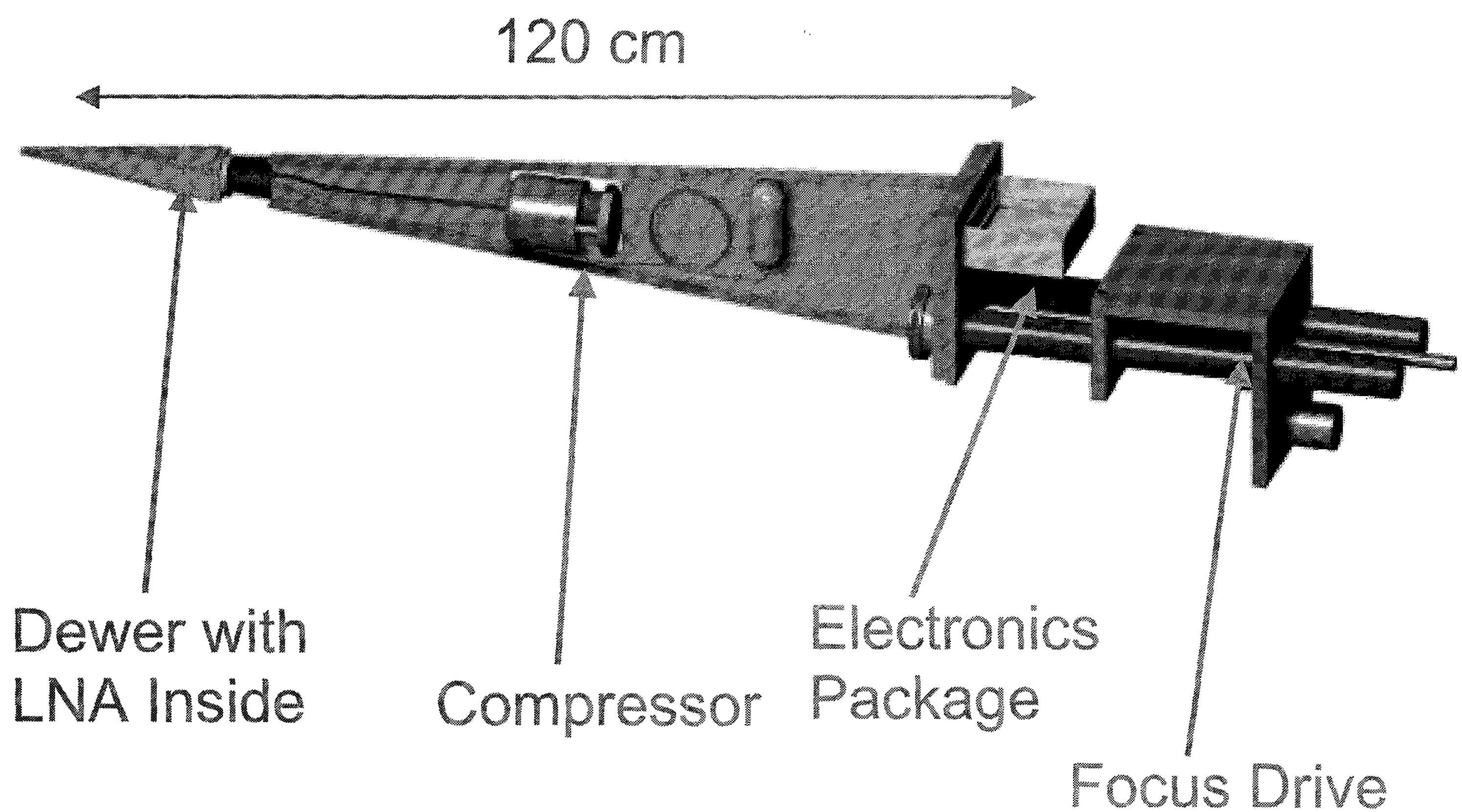
Efficiency > 60% expected over entire frequency range

Zig Zag
Log Periodic
Feed



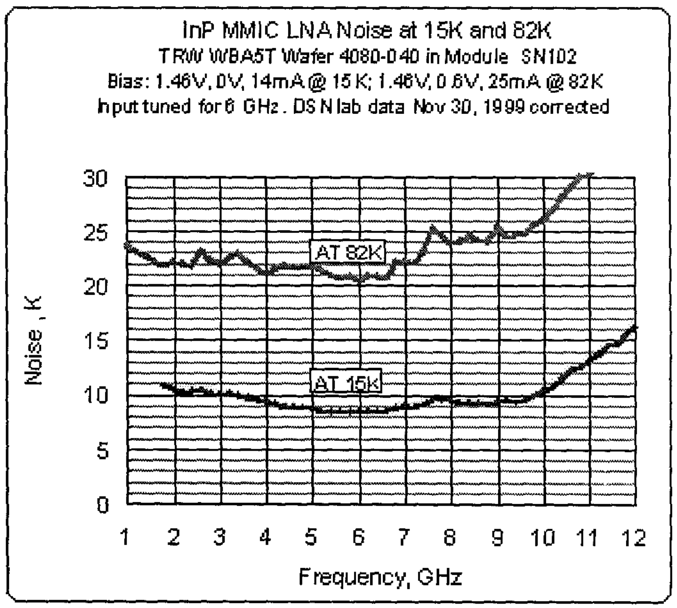
Revolutionary Ultra-Wideband Low Noise Receiver System for the ATA

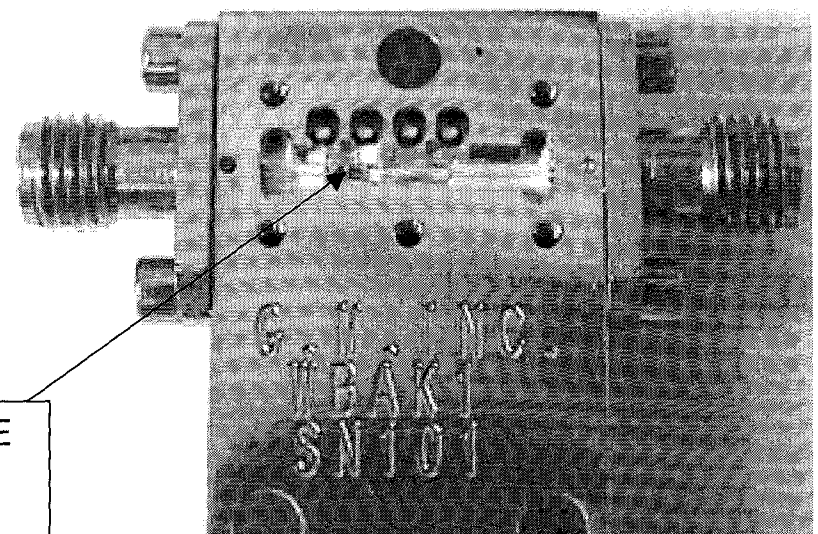
The structure shown below fits within the pyramidal log-periodic feed and connects to the feed tip. A miniature pulse-tube cryocooler is used to cool the LNA to 60K for <15K noise from 0.5 to 11 GHz.



Low-Noise Amplifiers Under Development at Caltech and JPL

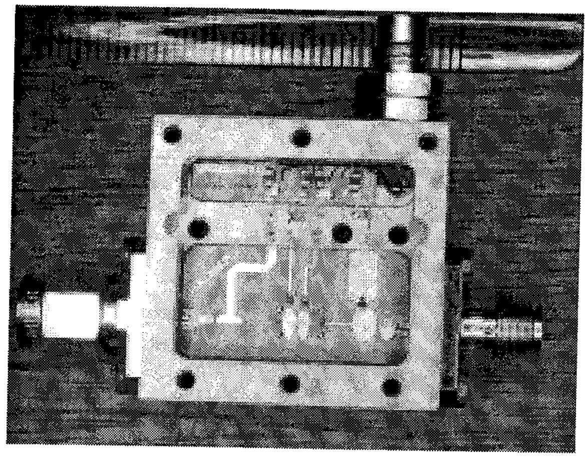
Frequency Range, GHz	Application	Noise
.5-11	ATA	23K @ 80K now, 15K later
4-12	ALMA IF	4K @ 4K, good input match
8-20	SIS IF Amplifer	10K @ 4K, good input match
1-60	NASA Atmospheric Sensor	400K @ 300K, 40K @ 15K
90-110	Planck, Cosmic Background	35K @ 15K
100-140	Atmospheric Sensor	600K @ 300K
170-210	Atmospheric Sensor	1500K @ 300K



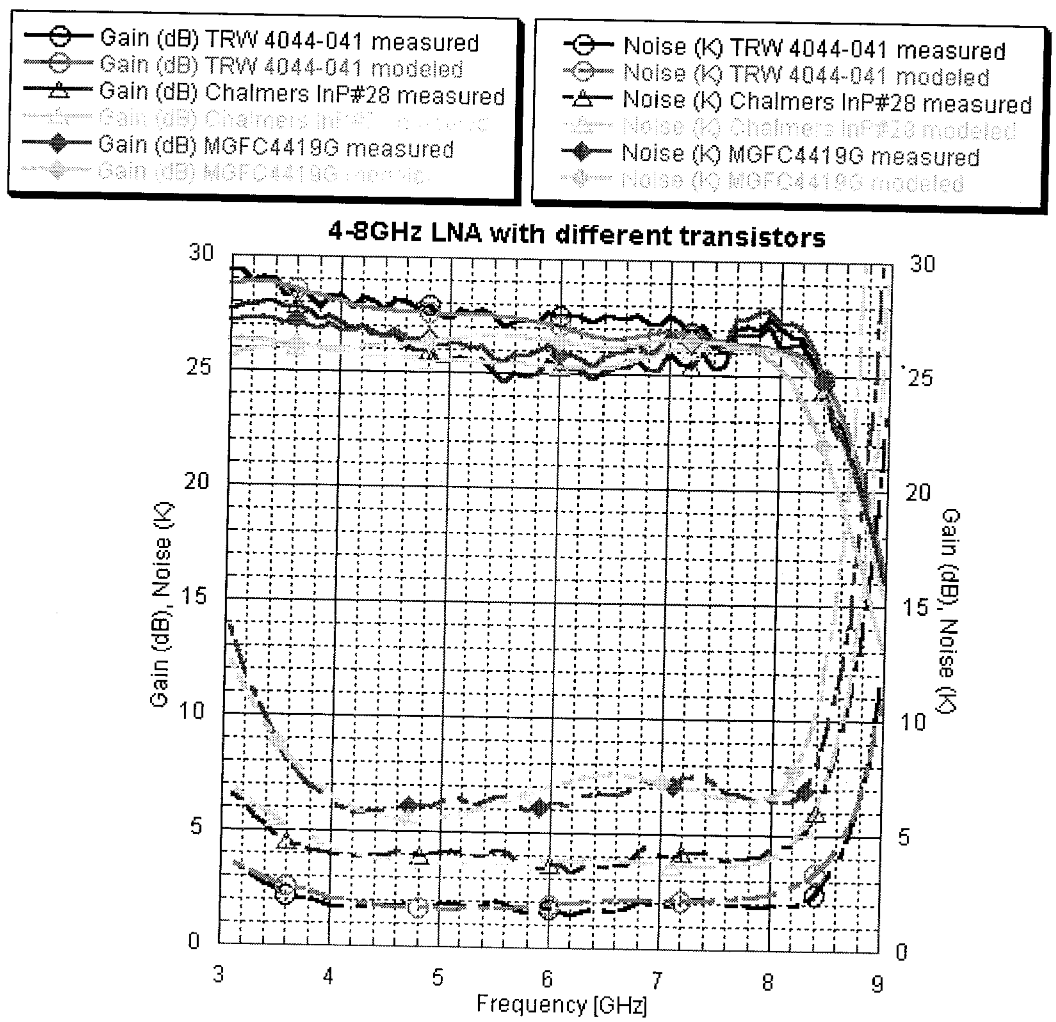


SINGLE CHIP LNA

Chalmers 4-8 GHz Cryogenic Low Noise Amplifier



World record 2K noise temperature, measured in 4 laboratories, achieved with TRW 0.1um InP HEMT



SKA Cost Equation Spread Sheet

Rows are for input or computed parameters such as cost coefficients or performance parameters

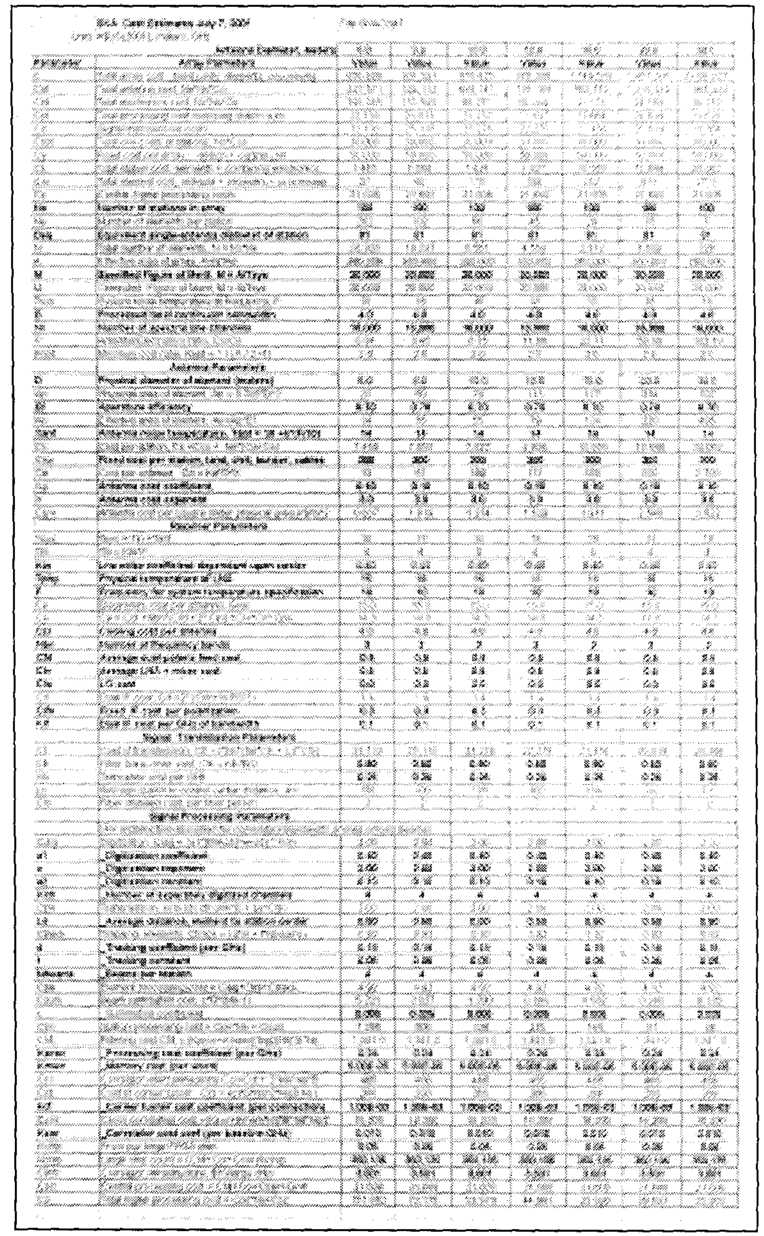
Columns are for varying antenna diameters

Sheets are for varying major parameters such as cryogenic temperature or era of electronics costs.

Output of the program is the total cost and cost of each subsystem. The Aeff/Tsys is constrained at 20,000 by computing the number of antennas needed for each station.

Parameters – There are 14 performance parameters and 19 cost parameters listed on the next page

Models – Details are in the equations in the spreadsheet. Antenna cost is 0.1*D^3 K$.



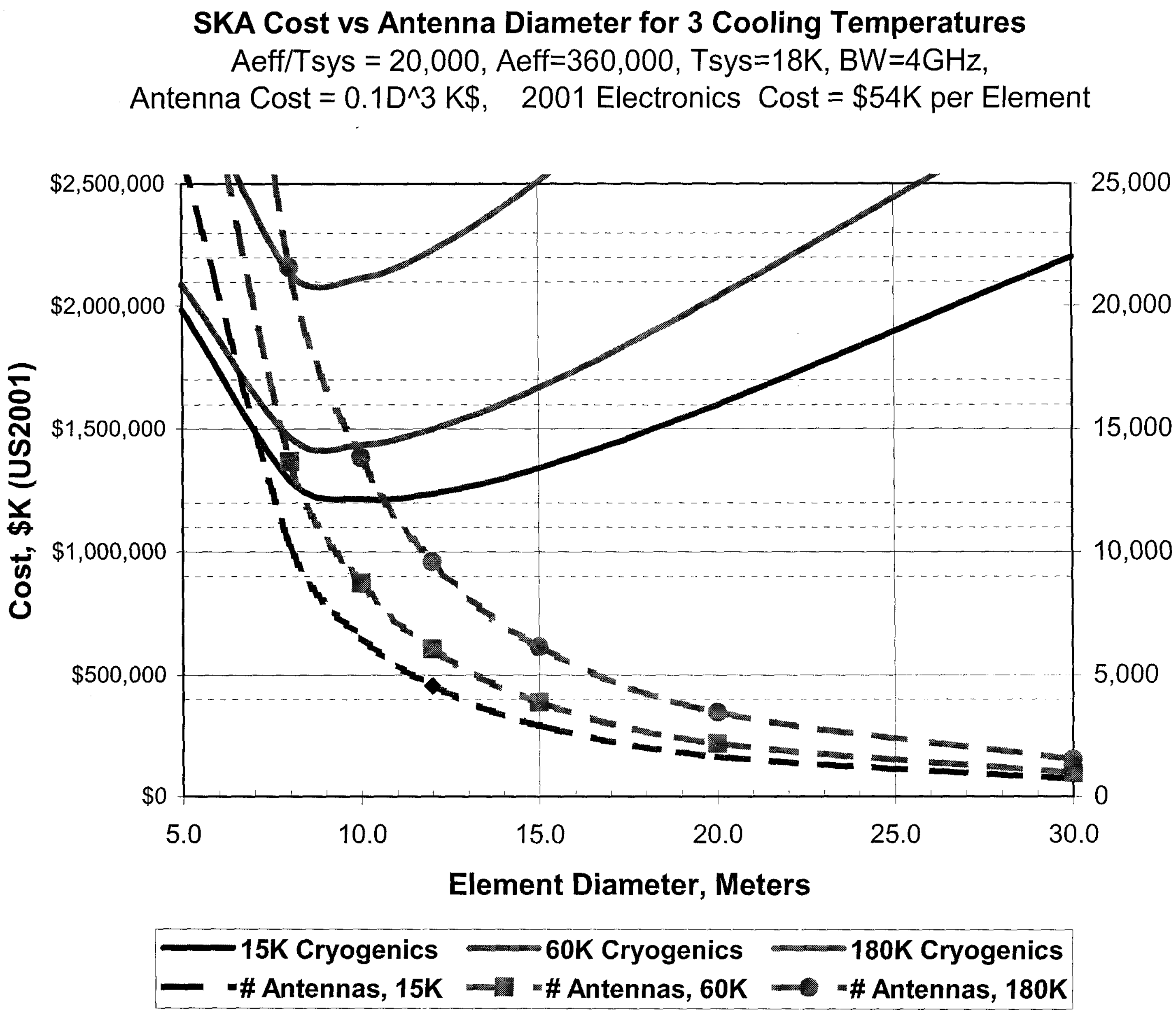
SKA Cost Equation Input Parameters

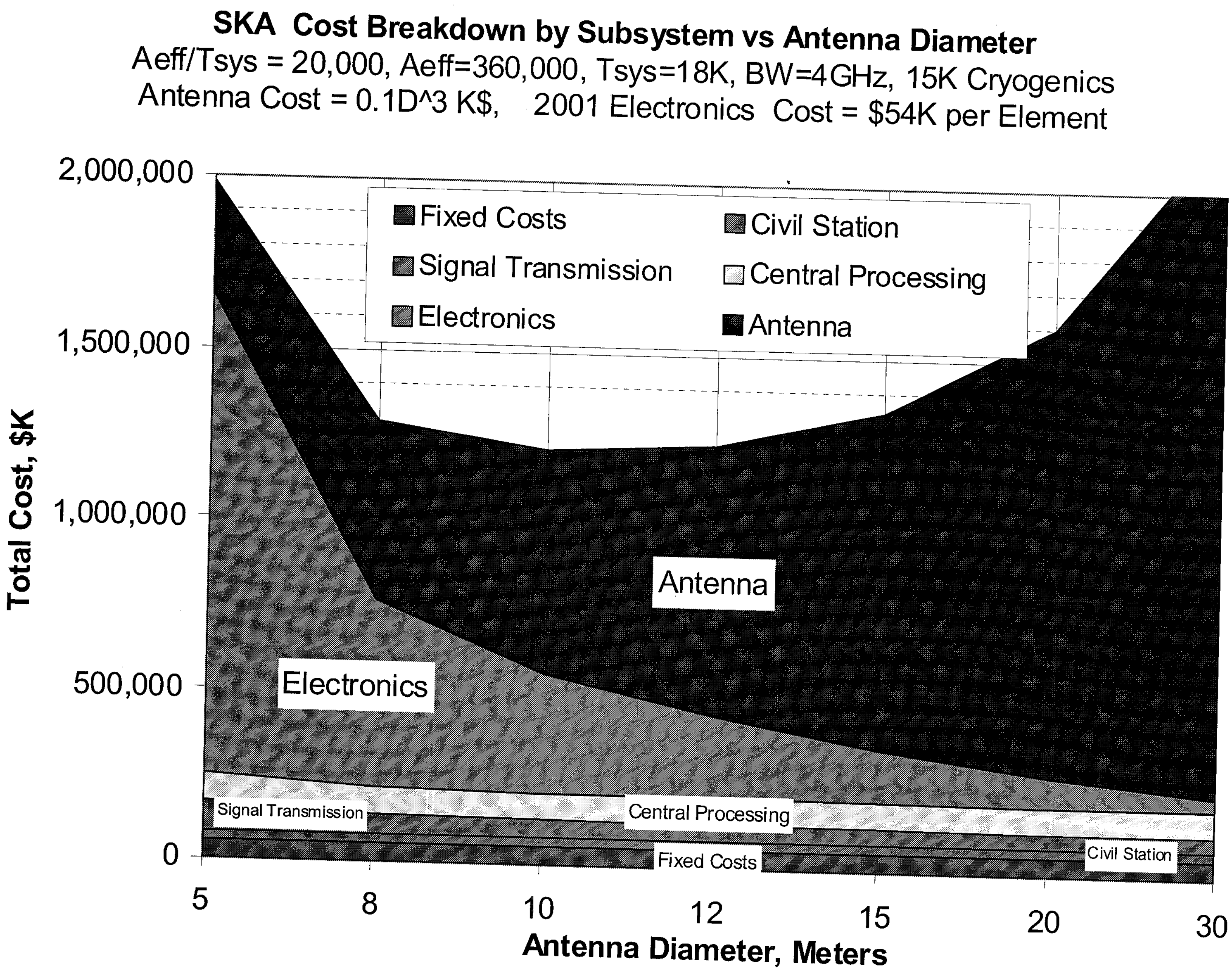
Units: K$US(2001), meters, GHz

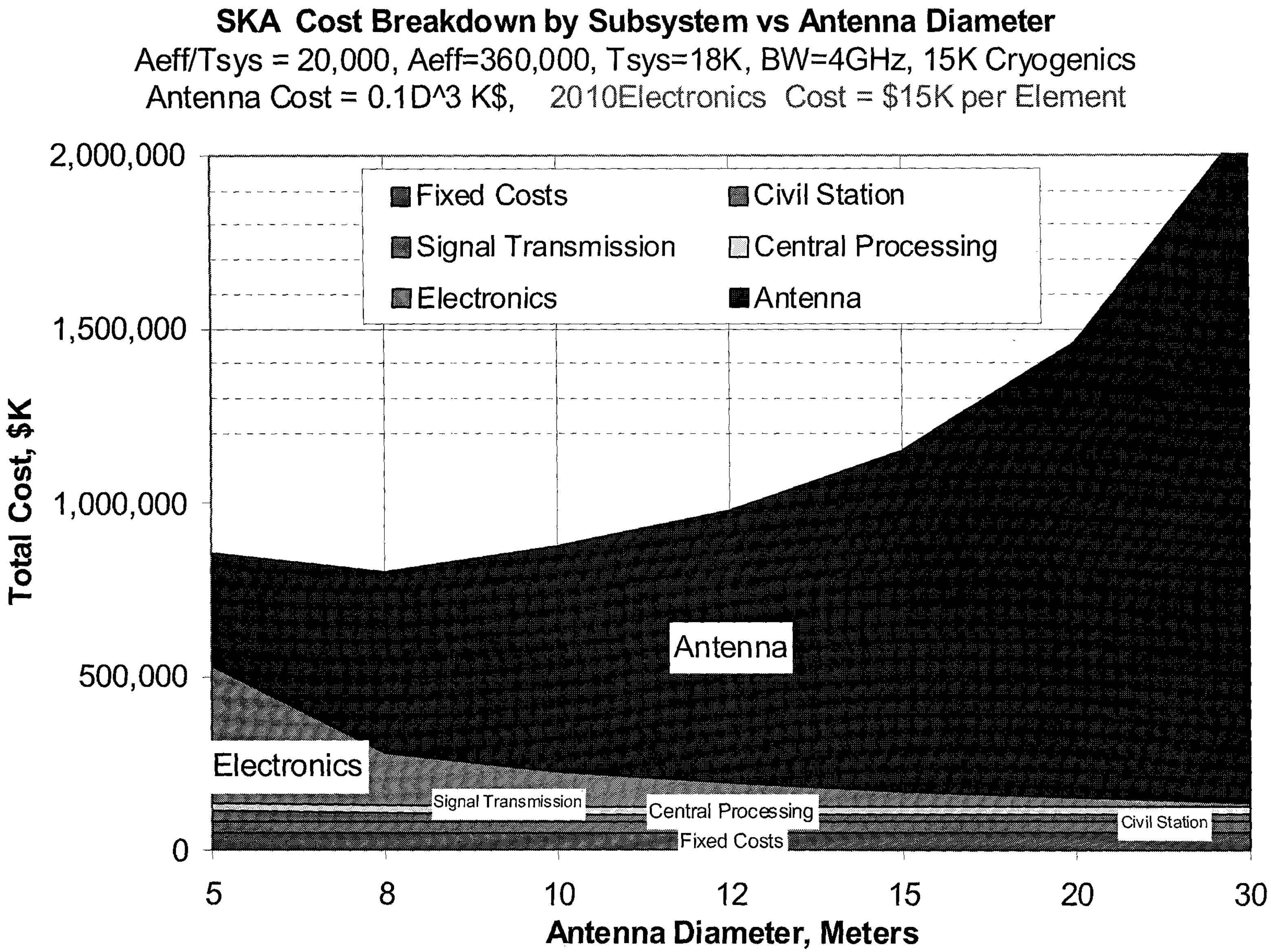
Param	Array Performance Parameters	Default Value
Ns	Number of stations in array	100
M	Specified Figure of Merit, M = A/Tsys	20,000
B	Processed total continuum bandwidth	4.0
Nl	Number of spectral line channels	16,000
D	Physical diameter of element (meters)	10.0
Ef	Aperature efficiency	0.70
Tant	Antenna noise temperature, Tant = 10	14
Kln	Lna noise coefficient dependant upon	0.40
Tphy	Physical temperature of LNA	15
F	Frequency for system temperature spe	10
Nbn	Number of frequency bands	3
Kch	_Number of separately digitized chann	4
Le	_Average distance, element to station	0.50
Nbeam	_Beams per station	4

Param	Array Cost Parameters	Default Value
Cso	Fixed cost per station, land, civil,	300
Ka	Antenna cost coefficient,	0.10
X	Antenna cost exponent	3.0
Ccl	Cooling cost per antenna	20.0
Cfd	Average dual-polariz feed cost	2.0
Cln	Average LNA + mixer cost	0.8
Clo	LO cost	3.0
Cifo	Fixed IF cost per polarization	1.0
Kif	Dual IF cost per GHz of bandwidt	0.2
a1	_Digitization coefficient	2.00
e	_Digitization exponent	2.00
a2	_Digitization constant	0.50
d	_Tracking coefficient (per GHz)	0.72
f	_Tracking constant	0.10
Kproc	_Processing cost coefficient (per	0.48
Kmem	_Memory cost (per word)	2.10E-04
kct	_Corner turner cost coefficient (p	1.00E-03
Kcor	_Correlator cost coef (per baselin	0.024
Kchip	Price per large FPGA chip	0.14

Color code:
Purple: correction of error since previous version.
Blue: change to value or formula since previous version.
Red: variable whose value changes across this sheet
Green: variable whose value is different from previous sheet
Bold type: input parameter; normal type means value is calculated.


SKA Cost vs Antenna Diameter for 3 Cooling Temperatures
Aeff/Tsys = 20,000, Aeff=360,000, Tsys=18K, BW=4GHz,
Antenna Cost = 0.1D^3 K$, 2001 Electronics Cost = $54K per Element
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$0
25,000
20,000
15,000
10,000
5,000
0
Cost, $K (US2001)
Number of Antennas
5.0
10.0
15.0
20.0
25.0
30.0
Element Diameter, Meters
15K Cryogenics
60K Cryogenics
180K Cryogenics
Antennas, 15K
Antennas, 60K
Antennas, 180K


SKA Cost Breakdown by Subsystem vs Antenna Diameter
Aeff/Tsys = 20,000, Aeff=360,000, Tsys=18K, BW=4GHz, 15K Cryogenics
Antenna Cost = 0.1D^3 K$, 2001 Electronics Cost = $54K per Element
Fixed Costs
Civil Station
Signal Transmission
Central Processing
Electronics
Antenna
2,000,000
1,500,000
1,000,000
500,000
0
Total Cost, $K
Antenna
Electronics
Signal Transmission
Central Processing
Fixed Costs
Civil Station
5
8
10
12
15
20
30
Antenna Diameter, Meters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Aeff/Tsys = 20,000, Aeff=360,000, Tsys=18K, BW=4GHz, 15K Cryogenics
Antenna Cost = 0.1D^3 K$, 2010Electronics Cost = $15K per Element
Fixed Costs
Civil Station
Signal Transmission
Central Processing
Electronics
Antenna
Total Cost, $K
2,000,000
1,500,000
1,000,000
500,000
0
Antenna
Electronics
Signal Transmission
Central Processing
Civil Station
Fixed Costs
5
8
10
12
15
20
30
Antenna Diameter, Meters

SKA for NASA – Overview Summary

- The present DSN capability places severe constraints on deep space science due to data rate limits and spacecraft antenna and power requirements.
- The DSN is saddled with aging facilities which are costly to maintain and is faced with increasing demands from more complex and data-rich missions.
- Construction of antennas larger that 70 or 100m is not cost effective compared with arrays of smaller antennas.
- Compared to the radio astronomy community the DSN has little experience with arrays – a learning period is required to provide know-how and management confidence.
- Long-range development of the DSN is concentrated in optical technology which has limitations due to pointing requirements and high quantum-limited noise.
- There is a ground swell of interest by NASA and JPL scientists in the far-reaching benefits of a SKA to space science. The factor of 100 increase in sensitivity has exciting potential.
- No new space exploration program within NASA wants to put the program at risk by requiring a $1B SKA yet the collective benefits to many programs over a 30+ year lifetime make very sound business sense.

DSN Situation Summary

- Present data rate from a Mars Lander to a 70m on earth is in the slow modem range – 1 to 10 kbps
- The data rate can be expanded to 10 - 1000 kbps with a Mars orbiting relay.
- The most cost effective way to increase the data rate to either a lander or an orbiting relay is by increasing the collecting area on earth
- Antennas larger than 70 to 100m are not cost effective because cost increases as D^2.7. A 140m antenna cost more that two 100m antennas.
- Arrays are the best way to increase antenna area in terms of cost, flexibility, and soft-failure. The minimum cost array is one in which the antenna cost is approximately twice the electronics cost. A rough estimate follows:

Electronics Cost per Element	Optimum Antenna	Total Cost For 10 x 70m
$10M	34m	40 x 34m, $1.0B
$1M	17m	160 x 17m, $0.5B
$100K	8.5m	640x8.5m, $0.3B

Objectives of a JPL DSN Array Technology Development Program

- **Liaison** with SKA, ATA, and eVLA array development tasks; assess technology and joint use for NASA applications.

- **Determine array cost vs antenna diameter** and electronics cost.

- **Verify cost** by fabrication and test of an array element followed by a prototype array.

- **Perform up-link phasing** experiments to gain experience and assess calibration burden.

- **Develop management confidence** in communication arrays by forming a group with the core expertise needed for implementation.

Goals for a JPL SKA/DSN Development Program

System Design

- Design interfaces to DSN user and science community
- Find optimum antenna element size and array configuration
- Participate in the SKA development

Antenna Manufacture

- Develop manufacturing technology to reach $600/m^2 cost target
- Rotating antenna turntable – conceptual design and cost estimate.
- Monitor ATA 350x6m manufacture
- Construct small antenna prototypes to verify cost and performance

Transmitter Design

- Design, fabricate, and test solid state 7 and 33 GHz HPA's (100W, 5W)
- Develop diplexer and exciter
- Develop geosynchronous satellite monitor receiver for transmitter phasing

Receiver Development

- Develop low cost MMIC LNA's , feed, and cryogenics; target $10K

Connectivity

- Develop satellite relay LO distribution and fiber-optic signal transmission

Signal Processing

- Design and prototype digital beam former and correlator

21st Century DSN Visions

The DSN should not only support, but should stimulate and enable the exploration of the solar system with large increases in data flow to both scientists and the public.

Year	Developmental Milestones	Operational System	Landmark Capability
2010	Optical link demos Prototype array demo	Robust 70m equivalents at Ka band at 3 DSN sites. IPN protocols in use	Reliable service to all planned missions in decade. Routine use of orbiting relays.
2020	Robust, low-cost 8 Gbt/s, W-band transceivers	10 x 70m equivalent array performance; optical links to outer planets	Virtual presence HDTV exploration of outer planets
2030	Interstellar transmitters, MEMs based receivers, Single-electron transistors	Square-KM arrays and optical links at 3 sites;	Detection of radio activity from identified earth-like planets